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A review on thermal response test of ground-coupled heat pump systems

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ABSTRACT

With the attractive advantages of high efficiency and environmental friendliness, the ground-coupled heat pump system (GCHPs) has been widely applied in various buildings around the world in recent years, and the knowledge of underground thermal properties is a prerequisite for correct design of GCHPs. As an effective way to obtain thermal properties, thermal response test (TRT) has become a routine tool for the design of larger plants with ground heat exchangers (GHEs). This paper summarizes the specifications for in situ TRT, including test setup, minimum duration, heat input rate etc., analyzes the mathematical models currently available for GHE in TRT, and compares the parameter identification methods which are necessary to obtain reasonable properties according to in situ TRT data. In addition, this paper discusses and summarizes the shortages and imperfects of the current research on TRT and gives some recommendations for future work.

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1. Introduction

Ground-coupled heat pump system (GCHPs) has been recognized as being among the most energy efficient systems for space heating and cooling in residential and commercial buildings [1–5]. GCHPs consist of a conventional heat pump coupled with a ground heat exchanger (GHE) where water or a water–antifreeze mixture exchanges heat with the ground. GHE is responsible for a major part of the initial cost of these systems and careful design procedures are needed not to overestimate borehole length which has a direct impact on the efficiency of GCHPs.

The knowledge of underground thermal properties is a prerequisite for correct design of GHE. The two important parameters are the soil thermal conductivity and borehole thermal resistance which is decided by borehole diameter, pipe size and configuration, pipe material, and the filling inside the borehole [6], so a larger soil thermal conductivity and a small borehole thermal resistance allow the heat to be exchanged at a larger rate for a given borehole. Calculations by Kavanaugh [7] indicated a 10% error in soil thermal conductivity and diffusivity result in a 4.5–5.8% error in the design of borehole length and 1% change in cooling capacity of GCHPs. Because of the two important parameters, in situ tests are often performed on a test borehole for larger commercial installations. At an early stage, e.g. a pre-study, geological maps and tabled thermal properties might be enough. In fact, more detailed studies require accurate determination of thermal properties. Several methods can be used to estimate ground thermal properties. These include soil and rock identification [8], experimental testing of drill cuttings [9], in situ probes [10], and inverse heat conduction models. The most common method to determine thermal properties, which was first presented in 1983 by Mogensen who suggested a system with a chilled heat carrier fluid [11], is thermal response test (TRT). The first mobile test rigs for TRT were developed independently at Luleå Technical University, Sweden [12] and at Oklahoma State University, US [13]. With the development of TRT technology, the recent developed equipment has been reduced in size to fit into suitcase-sized container from mobile test rigs housed on a trailer [14].

With the application of GCHPs in the world, TRT is now widely spread in Europe, America, Oceania, Asia and Africa. Sanner et al. [15] reviewed 70 TRT-rigs exist in Europe alone, Worldwide, the main market for TRT outside Europe is in the United States and Canada, with China, Japan and South Korea also seeing TRT done. At the same time, many researchers have developed mobile test facilities for this purpose, in different regions of the world, including Japan [16], Cyprus [17], Saudi Arabia [18], Syria [19], Algeria [20] and elsewhere. Up to now, TRT has become routine practice for determining the ground thermal properties for the design of GHE in some countries. As the design of GCHPs [21], it is necessary for TRT to regulate standardization and quality insurance. A first propose for a guidelines for TRT have been developed by the working group of Annex 13 "*wells and boreholes*" [22] of the Implementing Agreement on Energy Conservation through Energy Storage of the International Energy Agency (IEA) [15], and the guidelines laid down by ASHRAE [23] and IGSHPA [24] were all intended to comply with worldwide. Recommended test specifications were also listed in ASHARE [25]. In China, TRT has been required in the GCHPs project whose building area is more than 5000 m^2 according to technical code for GCHPs [26].

In this paper, the specifications for in situ TRT are reviewed. Next, modeling approaches of GHE and parameter identification methods applied to TRT are summarized based on the available references. Finally, the present paper proposes some suggestions on development and application of TRT for future work, such as the development of more detailed model for GHE, data analysis study on unexpected events in TRT, and distributed thermal response test (DTRT).

2. The specifications for in situ TRT

Even though in situ TRT has become a standard practice by use of a single pilot borehole, the issue of test accuracy for in situ TRT has received more attention [27]. So an advanced test setup and strict test conditions are raised for in situ TRT.

2.1. Test setup

An in situ test is typically performed on a vertical GHE with approximately the same diameter and depth as the heat exchangers planned for the site. The installation of a vertical GHE consists in drilling a well in which a single, double or coaxial polyethylene pipes are buried till a planned depth. The space between the pipes and the borehole wall is usually filled with heat transfer enhancing grout material. The equipment for an in situ test is illustrated in Fig. 1, where an electric heater at the surface serves as a controlled heat source. Water is pumped through the U-pipe and exchanges

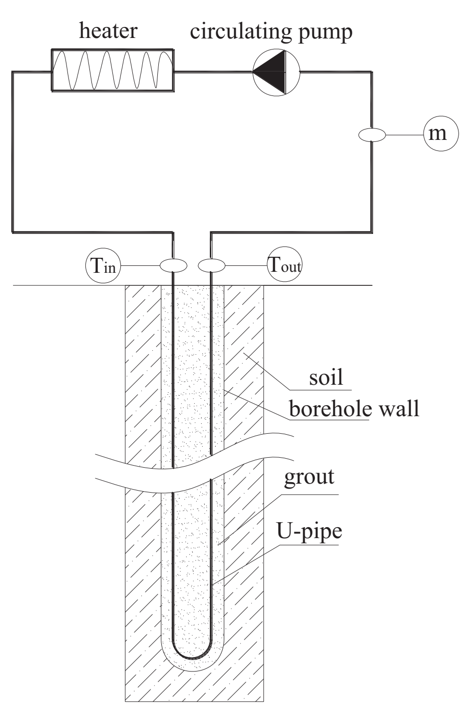

Fig. 1. Typical borehole test setup.

Nomenclature

b	constant (dimensionless)
C	volumetric heat capacities (J/(m^3 °C))
D	length along the piping between the temperature probe location and the borehole inlet or outlet (m)
d	diameter(m)
$erfc$	Gauss error function
Fo	Fourier constant (dimensionless)
G	dimensionless G-function
H	borehole depth length (m)
h	convective heat transfer coefficient (W/(m^2 °C))
J	Bessel function of the first kind
K	hydraulic conductivity (W/(m °C)),
k	the slope of the line (dimensionless)
l	depth (m)
m	flow rate of circulating pump (kg/s)
nl	number of U-pipe legs in a borehole
Pr	Prandtl number
q_l	heating rate per borehole length (W/m)
R	heat transfer resistance ((m °C)/W)
Re	Reynolds number
r	distance from the borehole axis (m)
T	temperature (°C)
t	time (s)
Y	Bessel function of the second kind
z	axial coordinate (m)

Greek letters

λ	thermal conductivity (W/(m °C))
α	thermal diffusivity (m^2/h)
$\gamma, \varepsilon, u, w$	constant (dimensionless)
η	dimensionless parameter (dimensionless)
θ	angle (deg)

Subscripts

0	initial
a	ambient air
b	borehole or borehole wall
E	end
ef	effective
f	fluid
g	grout
i	inner
LS	line source
num	numerical
o	outer
p	pipe
rec	recovery
s	soil
ex	experiment
in	inlet of the U-pipe
out	outlet of the U-pipe
sim	simulation

heat with the ground, while the inlet and outlet fluid temperatures are measured. The average of these two instantaneous temperature readings is usually taken to represent the average temperature in GHE at a given time. Although an electrical heater is usually used as the heat source, in situ tests have also been performed with other equipments. The studies conducted by Witte et al. [28] and Shan Kui et al. [29] proposed a reversible heat pump to heat or cool the circulating fluid through GHE. A new ground source heat pump test facility has been developed at Chalmers University of Technology, Sweden [30]. The new test facility has shown its flexibility in conducting TRTs. Issues like repeatability and reproducibility of TRTs can be comprehensively studied using various alternative approaches. The installed electric resistance heater can be used to conduct the thermal response testing in the heat injection mode. It is also possible to conduct TRTs in heat extraction mode using heat pump. Particularly, it can conduct TRTs using brine at constant input temperature to the boreholes. The test facility provides a unique opportunity to study thermal properties, including undisturbed ground temperature, ground thermal conductivity and borehole thermal resistance of nine boreholes in close proximity.

For a given heat input rate, the recorded average temperature rise of TRT will be steeper for soil with lower thermal conductivity, because the soil does not conduct the heat away from the borehole as quickly as in the case of higher soil thermal conductivity. Thus, the transient temperature of the ground loop together with the heat input rate measurements contains information about the soil thermal conductivity. In addition to soil thermal conductivity, the loop temperature curve is also influenced by the borehole parameters such as grout thermal conductivity, borehole diameter, and the location of the U-pipes in the borehole. All of these effects can be lumped together into a borehole thermal resistance.

IGSHPA presented the latest guideline for the site and test equipment of TRT [24], which can be found in ASHRAE handbook on HVAC application [25]. At first, soil classification and Soil Conservation Survey (SCS) for country/parish data should be obtained from the local SCS office. Secondly, a minimum delay of 5 days shall be observed between loop grouting and test start up. At last, for test equipment, entering/leaving water temperature shall be measured with ± 0.28 °C combined transducer–recorder accuracy, and heat input rate shall be measured with 2% combined transducer–recorder accuracy of reading (not full scale accuracy). Simultaneously, piping length between the test unit and the U-bend shall be equal to or less than 1.22 m per leg, pipe and all hydronic components within the test unit shall be sufficiently insulated to minimize ambient heat loss.

2.2. The undisturbed soil temperature

The undisturbed soil temperature is one of the most important parameters in the design of GCHPs, and a good estimate for the undisturbed soil temperature is necessary for a correct design of GHE. At the same time, it is required to calculate the borehole resistance from the field test data. Therefore, the undisturbed soil temperature should be determined accurately before TRT has started.

In fact, the undisturbed soil temperature commonly increases with depth due to the geothermal gradient. The earlier study shows it is not necessary to consider the temperature gradient along the borehole [31]. The mean temperature along the borehole is a good approximation of a homogeneous undisturbed soil temperature around the borehole. Gehlin and Nordell [31] discussed the two ways to determine the undisturbed soil temperature in detail, both methods require that the borehole be at thermal equilibrium with the surrounding ground. The common way to determine the undisturbed soil temperature is temperature loggings in the borehole or by circulating the heat carrier without heating for 10–30 min before the heater is switched on during TRT. The mean fluid temperature corresponds to the undisturbed ground temperature, this way has been applied in TRT [19,32,33]. However, even though no heat is rejected by the heater in 10–30 min, there will be some

heat gain to the system from pump work. Therefore, Kavanaugh recommended activating the pump and recording the minimum temperature as a good estimate of the undisturbed soil temperature [23]. ASHARE introduced that another alternative measurement is recording the temperature of the liquid as it exits the loop immediately following startup of the pump to circulate the fluid [25]. Another way is lowering a thermocouple down the water-filled U-pipe before the measurement has started. The temperature is measured every few meters along the U-pipe and the reading is used to calculate an arithmetic mean borehole temperature, i.e., the undisturbed soil temperature. This way had been introduced in Chinese technical code for GCHPs [26].

In the recent study on the initial soil temperature, the topic has been discussed that the geothermal gradient cannot be neglected. The geothermal gradient varies over the world and is normally in the range 0.5–3 °C per 100 m. To analyze the effects of the depth-dependent initial temperature distribution on the TRT result, Wagner et al. [34] estimated the soil thermal conductivity and borehole thermal resistance based on the artificial TRT data sets generated by a finite element model of a double U-pipe GHE with a typical geothermal gradient (0 °C per 100 m to 5.22 °C per100 m). The outcome demonstrates that a depth-dependent initial temperature field prevents reliable line source based TRT evaluation. The geothermal gradient influences the horizontal temperature gradient towards GHE. The amplified depth-dependent heat propagation which cannot be considered by the line source theory leads to an apparently higher thermal conductivity than the real one, the estimation error may exceed 10% for a gradient of 5.22 °C per 100 m, The study of Wagner et al. [34] clearly showed the limits of the standard TRT evaluation when the test performed is influenced by extreme high geothermal gradients. Sanner et al. [35] suggested more sophisticated TRT with additional information, e.g. vertical thermal conductivity distribution along the GHE and increased accuracy of the sensors should be developed, this is called enhanced geothermal response test (EGRT). Furthermore, Sanner et al. [35] proposed the temperature thermocouple inside the GHE could only be used before starting TRT in order to see the undisturbed ground conditions, and it help to identify zones of higher or lower heat transport along the borehole axis by combining with two temperature thermocouples used after TRT had been stopped. Based on the experiences from about 20 TRTs applied temperature thermocouple inside the GHE, Liebel et al. [36] suggested that a temperature profile should be measured before a TRT to find the undisturbed soil temperature. The study also shows measuring the temperature profile inside the GHE after a TRT can add valuable information to the study. In addition to measure the undisturbed soil temperature, it has been recently proposed to measure temperature variations inside the GHE during a TRT to determine the thermal properties as a function of depth, which is possible to determine the vertical distribution of subsurface thermal conductivity when the distribution of geological units along the borehole is known [16,37]. Moreover, Rohner et al. [38] described a small wireless probe that is placed in a completed but not working borehole heat exchanger. By its own weight the probe sank to the bottom of the liquid filled U-pipe. The probe recorded temperature and pressure at pre-set time intervals during its descent. Then, the probe was flushed back to the surface using a small pump. Analysis of the data gave a vertical temperature profile along the borehole, Fig. 2 shows a typical measured temperature–depth profile, along with the geologic profile of the GHE borehole [38].

2.3. Minimum duration of TRT

Determining soil thermal properties is an inverse problem of heat transfer, and thermal properties in the vicinity of the GHE can only be estimated by evaluating the in situ recorded temperatures versus time in TRT. Therefore, the test duration of TRT must be sufficient to provide a valid estimation for soil thermal properties. Furthermore, there is a desire to have a prior estimate of the minimum test duration that yields valid result because the cost of a test increases with increasing duration. However, the minimum duration of a TRT is the subject of on-going debate, in the literature there are recommendations for 60 h [39], 50 h [13], 36–48 h [25] and 12–20 h [40].

Based on the analytical composite model (COM), Beier and Smith [41] developed a method to calculate minimum test duration required to estimate the soil thermal conductivity to within 10% of its long-term estimate. Their results show that the minimum test duration may vary significantly, depending on the GHE geometry and thermal properties. The required test duration increases significantly as the grout thermal conductivity decreases below the soil thermal conductivity. Also, the minimum test duration increases as the borehole thermal resistance increases. In another study, Bujok et al. [42] investigated effect of TRT duration on the precision of determining thermal conductivity and borehole resistance. The results showed that the average relative difference of thermal conductivity between the full 70 h TRT duration and shortened 24 h TRT duration was 6.53%, for borehole resistance, it was 7.76%. However, differences of results between 60 h and 70 h tests were approximately 1%. It is evident that shortening the test to 24 h in their case would have brought an acceptable amount of inaccuracy with regard to the dispersion of measured values obtained from the real test. Based on the time required for the temperature perturbation to reach a given radius of influence in hydraulic conductivity testing, Raymond et al. [43]

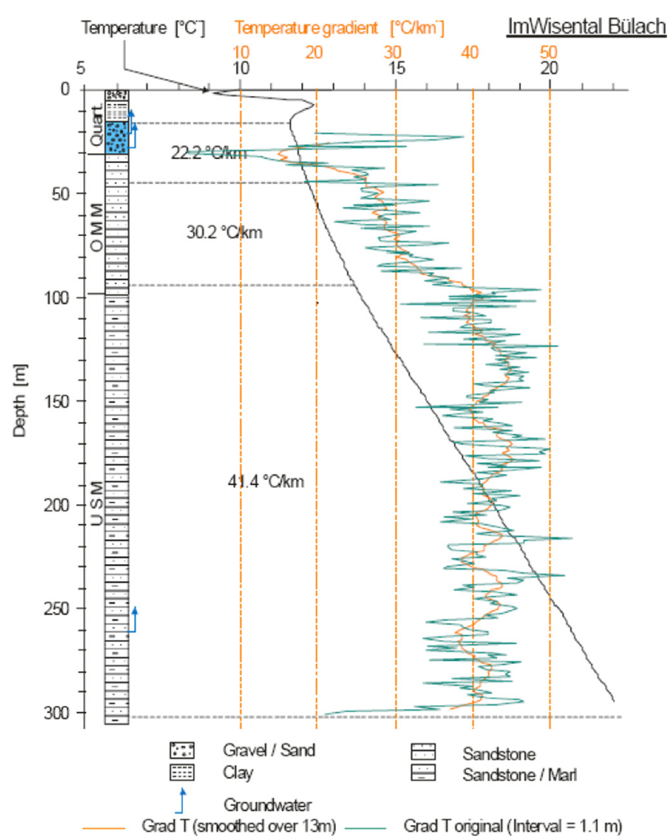

Fig. 2. GHE borehole Im Wiesental, Bülach near Zurich: Geologic column, measured temperatures (with gradient sections; black line), gradient calculated with the original measurement spacing of $\Delta z = 1.1$ m (blue line) and smoothed over $\Delta z = 13$ m [38]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

proposed an alternative method to determine the minimum test duration. Their experience suggested that estimating the test duration by assuming a radius of influence of 0.5–1.5 m provided sufficient temperature measurements to estimate thermal properties without requiring unnecessary large testing times. Signorelli et al. [44] compared the results from a 3-D finite element numerical model with those of a simple analytical line source solution and tested their sensitivity to the duration of the tests. Especially, the study concentrated on the influence of starting time, t_0, on the line-source evaluation, and the impact of the required length of data interval on the calculation of thermal conductivity. In the case, the simulated 200 h test from the numerical model was evaluated for increasing data interval lengths using different fixed starting times of 10 h, 20 h, 40 h, and 60 h, and variable end times of $t_0 < t_E \leq 200$ h. The end time of the evaluated interval, t_E, corresponds to the length of the test. Then, the errors corresponding to different starting time and increasing values of t_E are analyzed when the estimated thermal conductivities λ_{LS} are compared with the assumed value λ_{num} used in the numerical model to generate the synthetic TRT. The result shows that changes in t_0 have a stronger effect on accuracy than changes in t_E. As shown in Fig. 3, for $t_0 = 10$ h, the test must last at least 30 h for the error to drop below 10%, whereas at $t_0 = 60$ h, the error is close to zero, irrespective of the evaluated interval length. Starting the evaluation at $t_0 = 20$ h, the error can always be expected to be less than 10%. To illustrate the effect of temperature measurement errors in TRT on the estimate of thermal conductivity, a 0.1 °C white noise is superimposed on the synthetic thermal response. The λ_{LS} was then evaluated from the new data sets. For the case of $t_0 = 40$ h, the 95% confidence interval of these λ_{LS} evaluations is represented by the shaded area in Fig. 3, indicating that for small intervals (t_E is slightly higher than t_0) the accuracy of the evaluation is compromised. The deviation from λ_{num} ranges between 0% and $>10\%$, compared to the $<4\%$ under ideal conditions, although the effect of the applied temperature disturbance vanishes at later t_E. For the case of $t_0 = 10$ h, because of the strong temperature increase at early times (low t_0), the resulting confidence interval is smaller. At larger t_0, however, the influence of temperature disturbance on the accuracy of the λ_{LS} evaluation can become dominant. Therefore, small values of t_0 tend to underestimate the subsurface thermal conductivity, but show reduced sensitivity to temperature disturbances from actual temperature measurement errors. In contrast, high values of t_0 give good approximate values, but can be strongly affected by temperature variations.

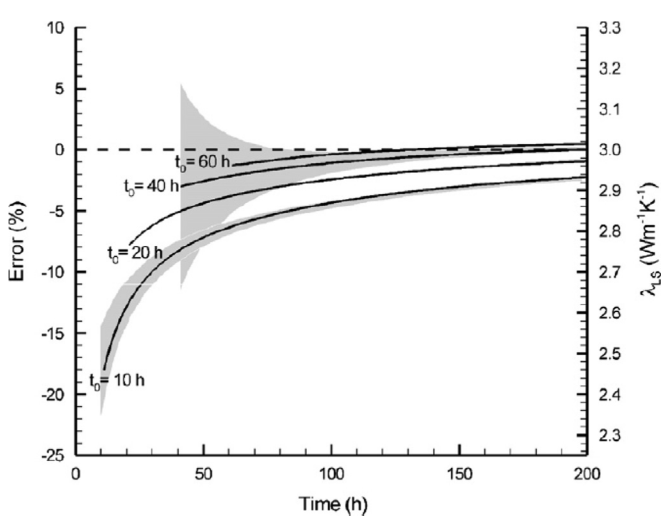

Fig. 3. Results of the study to determine the TRT duration required to obtain a 10% accuracy using the line-source model. Plotted is the difference between the computed thermal conductivity, λ_{LS}, and that assumed in the numerical model, λ_{num}. The starting point, t_0, for the different evaluated data intervals is set at 10, 20, 40, and 60 h. The end time, t_E, is varied from (t_0+1) h up to 200 h. Shading shows the region corresponding to the 95% confidence interval, when a 0.1 °C white noise is superimposed on the synthetic thermal response [44].

2.4. Heat input rate of the electric heater

In the ideal TRT, heat is generated by an electric heater and rejected to the ground at nearly a constant rate whose load should aim for a temperature development in the heat carrier fluid as similar as possible to that of the fact GCHPs. ASHARE [25] recommended acceptable power quality could be obtained when the standard deviation $\leq 1.5\%$ of average power and the maximum variation (spikes) $\leq 10.0\%$ of average power. When the deviations are larger, acceptable results could be obtained if the maximum deviation of average loop temperature is ≤ 0.28 °C. The heat rate should be 49.2–82 W per meter of borehole. Actually, the heat rate is never absolutely constant but varies with changes in voltage to an electric heater. If the electric power is from a local utility line or a portable generator, the variations in electric power cause significant changes in the heat rate. In order to remove variable-rate effects for TRT, Austin et al. [13] used numerical parameter estimation methods to estimate soil thermal conductivity in variable-rate tests. Moreover, Beier and Smith [45] adapt the Laplace domain approach to take out the effect of variable heat rate during an in situ test without forcing the user to choose the method of analysis beforehand. The deconvolution method serves as a preprocessing step before applying a mathematical GHE model to determine soil conductivity and thermal resistance, which gives the engineer more flexibility in analyzing a test.

When electrical power outages, electric heater failures, or other unexpected events sometimes interrupt borehole tests before the test duration is sufficient to estimate soil thermal conductivity, if TRT is restarted immediately after the equipment problems are fixed, large swings in the heat rate to the ground-loop complicate the analysis of test. Most analysis methods assume a spatially uniform ground temperature at the start of the test, and this assumption is invalid if the test is restarted quickly. For an interrupted test, ASHARE [25] recommended a 10- to 12-day waiting period before retesting a borehole after a completed 48-h test and suggested the waiting period can be reduced in proportion to the reduced test time. Beier and Smith [46] described a method to quantify the time it took for the temperature curve to recover from the interruption. In the method, the recovery time from the interruption is given:

$$t_{rec} = \frac{-u + \sqrt{u^2 - 4\varepsilon w}}{2\varepsilon} \quad (1)$$

where $u = -[\varepsilon(t_1 + t_2) + t_2 - t_1]$, $w = \varepsilon t_1 t_2$, t_1 is the time when the heat rate suddenly goes to zero, and t_2 is the time when the power is restored. In the sandbox experiment, an 8 h interruption requires a recovery time of about 190 h after the beginning of the initial test. In fact, when calculated recovery time is long, it is necessary to shorten the required test time for longer interruptions and still provide an accurate estimate of the soil thermal conductivity. In 2008, the equivalent-time method for interrupted TRT was proposed by Beier [47]. By using this method and restarting the test immediately after the power was restored, one could save time and money compared with waiting for the initial heat pulse to dissipate before restarting. Different from Beier's study, the method proposed by Hu et al. [48] used superposition principle to solve the variable-rate heat input problem in TRT including the large power fluctuation and power failure, which was an unsteady method based on modified composite

model considering the unsteady-state heat transfer in the borehole.

Additionally, it was reported that TRT of variable-rate heat input was used to investigate GHEs for groundwater influences. Witte et al. [49] developed a new TRT protocol using controlled multi-power level heating and cooling pulses (MPL-HCP) in order to quantify groundwater effects on heat transport around a GHE. The test consists of reference experiment and the experiment with groundwater extraction, each test comprises three energy-pulses: two heat injections at different energy levels (1602–1606 W, 2446–2477 W) and one heat extraction pulse (1945–1947 W), and a recovery time interval between heat injection and heat extraction is 4 h. At the same time, duration of every pulse was kept virtually the same in the two experiments. The temperature evolution of both the experiments is shown in Fig. 4. The difference in temperature response is quite obvious, the experiment with groundwater flow shows a lower rate of temperature increase, which is more, pronounced during the second heat injection pulse. The estimated value for the complete data series shows a high overall conductivity for the groundwater extraction experiment. For the reference experiment there is no great difference between the estimated values for different periods. However, there is clearly a trend of increasing conductivity with the progression of the groundwater extraction experiment. The estimated borehole resistance values are in the same range for both experiments, notable is the borehole resistance is lower during the later heat-extraction pulse. For the groundwater extraction experiment, the estimated conductivity shows a relation with the temperature difference. Especially during the second heat injection pulse, the estimated conductivity is higher during the second part of the pulse. For the estimated borehole resistances no such dependence on the temperature difference is evident. Borehole resistance values during the heat extraction period are somewhat higher for the groundwater extraction experiment. Similar to the above procedure, Gustafsson and Westerlund [50] performed 4 different heat injection rate (75, 59, 40 and 21 W/m) in a nearly 600-h TRT in groundwater filled GHE. The parameter estimation was performed with the first injection rate period (75 W/m). Based on the estimated conductivity and borehole heat resistance, the mean fluid temperature was calculated, and it was contrasted with the measured value. The two mean fluid temperatures match in the first period, but is not valid for the whole measurement. Since this is in the fractured solid bedrock, the thermal resistance in the borehole changes

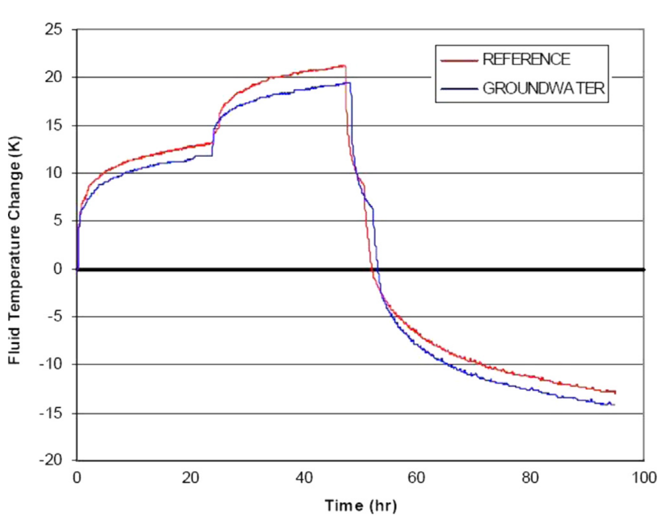

Fig. 4. Temperature change of heat transfer fluid temperature for the reference and groundwater extraction experiment [49].

when the injection rate is changed. It may also be noted that a larger difference in heat injection rate results in a larger difference between the measured and calculated mean fluid temperature. Therefore, the multi-injection rate thermal response test is shown to be a good method for detecting influences in the borehole as well as in the bedrock. Performing a measurement with 3–4 different heat injection rate periods makes it possible to detect fractured ground and to specify a relation between the thermal response and, e.g. the circulating fluid temperature.

2.5. Climatic conditions

There are many possible sources of error when performing an in situ TRT. Except for sensor errors and fluctuations of the heat rate, climatic conditions are one of the most important factors influencing the test results of TRT.

Climatic conditions affect mainly the connecting pipes between test equipment and GHE, the interior temperatures of the test equipment, and sometimes the upper part of the GHE in the ground. Insulation and sometimes shading is required to protect the connecting pipes. Because of the strong seasonal effect of natural ground temperature, the natural ground temperature may vary with the seasonal cycle weather conditions especially at the shallow zone. Additionally, with open or poorly grouted GHE, also rainwater intrusion may cause temperature changes. Wang et al. [51] proposed the heat-transfer performance of the GHE may be affected to a certain extent, and seasonal effect should be paid enough attention during TRT.

Based on the heat balances for the heat carrier fluid in TRT, T.V. Bandos et al. [52] proposed a method to account for climatic influence and efficiently subtract it from the data. In the method, the real mean fluid temperature in GHE can be written as

$$\overline{T_f} = \frac{T_{out}(t)+T_{in}(t)}{2} = T_a(t)(1-\cosh\eta) + \frac{e^{\eta}T_{ex,out}(t)+e^{-\eta}T_{ex,in}(t)}{2} \tag{2}$$

where $\eta = D/R_a C_f m$, it takes non-zero values in actual conditions of penetrating ambient influence, while its zero value is reached for the limiting case of perfect thermal insulation of the connecting pipes $R_a=\infty$ or $m=\infty$. Therefore, $\eta=0$ corresponds to the ideal test conditions without heat dissipation to the ambient, and Eq. (2) can be used to subtract climate influence from the TRT data when $\eta \neq 0$. The data obtained from the TRT are evaluated and compared by making use of finite line source model (FLSM), along with the above described method of accounting for the heat rate transmitted to ambient air, characterized by η. Fig. 5 plots the thermal conductivity estimates obtained by using the data in the intervals: from the [46–71] h to the [1–71] h (thus, t_0 varies from 1 h to 46 h). The length of estimation interval is changed by 1 h in a step-wise manner from 25 to 70 h the former interval corresponds to the late times of the test. As shown in Fig. 5, conventional data analysis (i.e., assuming no heat exchange between the ambient air and the fluid) gives significant differences between thermal conductivity estimates within the selected time intervals (when varying t_0 from 1 h to 46 h, while t_E=71 h). In contrast to this TRT estimate, the thermal conductivity curves are expected to flatten out below for large estimation intervals, especially, in this case,$\eta \neq 0$, the ground conductivity curve approaches a horizontal line with increasing length of time series, and fluctuations in ground thermal conductivity estimates with $\eta=0$ almost disappear. Therefore, the removal of the climatic effect successfully damped the oscillations of the ground conductivity estimates from the test data with increasing length of the time series. Application to TRT demonstrated that the atmospheric effect can distort the estimate of ground conductivity by a factor of one-third, while the estimated ground conductivity is within a 10% interval of the mean

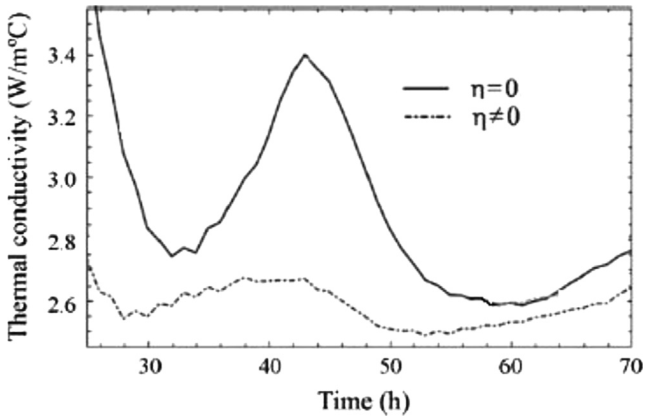

Fig. 5. Comparison between dependence of thermal conductivity on the time interval length from FLSM for the same test data when the end of the evaluation interval is fixed while its starting point increases: (i) without outside heat losses to the ambient air ($\eta = 0$) and (ii) with heat losses ($\eta = 0.006$) to the ambient air [52].

value. It had been shown that this proposed method of using the ambient temperature data in the analysis allows suppression of the influence of diurnal atmospheric conditions on the estimates of thermal conductivity and borehole resistance.

2.6. Impact of groundwater on TRT

Although heat conduction is the dominate mechanism of heat transfer between GHE and the surrounding soil, the movement of groundwater should not be ignored. Groundwater movement enhances heat transfer between the circulating fluid in the loop and the ground, so it can change the characteristic shape of the transient loop temperature curve in TRT. In layered sedimentary rocks, the thermal properties of individual layers can be variable and a homogeneous medium might not adequately represent the thermal properties of the layered system. When the permeability of the subsurface is sufficiently high, significant groundwater flow can lead to advective heat transport. The influence of groundwater flow on TRTs has been examined in experimental and theoretical studies.

Signorelli et al. [44] studied the impact of groundwater flow on TRT by use of a 3-D model and the FRACTure code [53]. The study showed that the subsurface conductivity could not be correctly evaluated from the data of an actual TRT without further analysis if there is significant groundwater flow, and the movement of water needs to be incorporated into the interpretation of TRT data. Gehlin and Hellström [54] studied the influence of groundwater flow on TRT in fractures. The results indicated that groundwater flow in fractures even at relatively low specific flow rates may cause significantly enhanced heat transfer. For GHE located in solid bedrock, the study of Gustafsson and Westerlund [50] showed only the borehole thermal resistance was influenced by the convective flow, an increase in heat input rate resulted in a decrease in resistance. The study from Liebel et al. [55] presented that forced convection enhanced the performance of GHE. The required borehole lengths decreased with increasing heat input rates during the TRT without pumping of groundwater due to increasing buoyancy-driven convection. An artificial convection stronger than buoyancy-driven convection during the TRT with pumping of groundwater reduced the required borehole length by 9–25% depending on the heat input rate.

Based on the moving line source theory [56] of GHE with groundwater advection, a model calibration approach for the TRT analysis was introduced by Wagner et al. [57], which was sensitive to conduction and advection. The presented analytical approach revealed that there was a systematical misfit between actual and estimated Darcy velocities and expanded the field of application of the TRT to advection-influenced conditions beyond a Darcy velocity of 0.1 m day^{-1}. Furthermore, Wagner et al. [58] proposed an advection sensitive TRT evaluation as a potential method to estimate Darcy velocity and integral aquifer hydraulic conductivity. For demonstrating the applicability, the correction term-based TRT evaluation [57] is integrated in a two-step fitting approach. Two measured TRT temperature time series, from a large-scale tank experiment and one from a standard in situ TRT are used to validate the new approach. Results for both the experiments reveal that temperature time series of a TRT can be used to determine hydraulic parameters. This changes the motivation of standard TRT application, which is mainly focused on thermal parameters, such as thermal conductivity and thermal borehole resistance, describing heat conduction from heated GHE. The conclusion is presented that thermal conduction and dispersion are much less sensitive than hydraulic parameters (i.e., hydraulic conductivity) for advection-influenced TRTs.

In order to analyze TRTs representing all processes relevant to TRT behavior: heat conduction, heat advection and mechanical thermal dispersion [59] in heterogeneous porous media, as well as non-uniform initial and boundary conditions, Raymond et al. [60] developed a modeling strategy to represent a GHE with the groundwater flow and heat transfer numerical simulator HydroGeoSphere [61] that can represent 3D groundwater flow and heat transfer in complex geological systems. The numerical model was successfully compared to an analysis performed in standard conditions with line source model (LSM) and then used to analyze a test performed in a geological setting where LSM assumptions cannot be justified. In this case, the numerical model provides a more reliable estimate of the thermal conductivity of the subsurface because it accounts for phenomena interacting with heat injected from the borehole. Furthermore, a new computer program MLU [62], used for pumping test analysis to determine hydraulic properties of layered aquifer systems, was adapted and verified to analyze TRTs with temperature measurements at depth in the GHE. The analysis of temperatures obtained with a layered numerical model for three cases indicated that recovery data can be used to assess the thermal conductivity of the layers. The analysis produced more accurate results for cases with small contrasts in thermal conductivity between the layers. Because TRTs involve a heat source that perturbs subsurface temperatures initially assumed to be at equilibrium, they are analogous to pumping tests in hydrogeology, where groundwater is pumped to perturb hydraulic heads in an aquifer [43]. A Taylor series [63] approximation of the well function is useful to evaluate the line-source exponential integral, and easily compute temperature increments caused by step heat injection using the superposition principle.

3. Mathematical models for GHE in TRT

A number of mathematical models for GHE in TRT have been recently reported, most of which were based on either analytical approaches or numerical methods. A few models were developed based on the incorporation of the analytical and numerical solutions, such as Eskilson's model [64]. In this section, the various models for GHE in TRT given in the literature are illustrated and analyzed.

3.1. Analytical approaches

3.1.1. Line source model

In many mathematical models of GHE in TRT, the most important model is line source model (LSM), based on the so-

called Kelvin line source theory, i.e. infinite line source model (ILSM) [65,66]. This simple model represents the starting point for discussing the estimation procedure embedded in the TRT and applied to a vertical GHE. In 1948, Ingersoll and Plass [67] improved ILSM to solve the heat transfer problem of GHE. In Ingersoll's theory, the heat transfer of GHE is simplified as the heat transfer of the heat source which has the same axis of the borehole. The model ignores the details of the complicated geometry of the U-pipe loop and the differences in thermal properties of the grout and soil. Therefore, the measured early-time temperature rise will likely deviate from the straight-line trend of the model. Instead, a borehole thermal resistance is used to represent the sum of all the thermal resistances inside the borehole between the circulating fluid and the soil.

For the ILSM [28,66,68,69], the mean temperature of the circulating fluid in the ground loop is approximated by

$$T_f(t)=T_0+\frac{q_l}{4\lambda_s\pi}\left[Ei\left(\frac{r_b^2C_s}{4\lambda_s t}\right)+4\pi\lambda_s R_b\right]=T_0+\frac{q_l}{4\lambda_s\pi}\left[\ln\left(\frac{4\lambda_s t}{\gamma r_b^2 C_s}\right)+4\pi\lambda_s R_b\right] \tag{3}$$

where $Ei(x)=\int_x^{\infty}(e^{-s}/s)ds$, which represents the exponential integral. The natural logarithm approximation on the right side of Eq. (3) is accurate to 5% when $(4\lambda_s t/r_b^2 C_s)>11$. Here, γ is a constant that is approximately equal to 1.78.

Based on the Eskilson's model [64], an analytical solution to the finite line source model (FLSM) has been developed by the Ground Source Heat Pump Research Group of Shandong Jianzhu University which considers the influences of the finite length of the borehole and the ground surface as a boundary, the mean temperature of the circulating fluid in the ground loop was given by Zeng et al. [70].

$$T_f(t)=T_0+\frac{q_l}{4\lambda_s\pi}\left[\int_0^H\left(\frac{erfc(\sqrt{((d_b/2))^2+((H/2)-l)^2}/2\sqrt{a_s t})}{\sqrt{(d_b/2)^2+((H/2)-l)^2}}-\frac{erfc((\sqrt{(d_b/2)^2+((H/2)+l)^2})/2\sqrt{a_s t})}{\sqrt{(d_b/2)^2+((H/2)+l)^2}}\right)dl+4\pi\lambda_s R_b\right] \tag{4}$$

In Eq. (4), it was shown that the circulating fluid temperature, where $r=r_b=d_b/2$, $\alpha_s=\lambda_s/C_s=\lambda_s/\rho_s c_s$, varies with time and borehole depth. The temperature at the middle of the borehole depth (l=0.5H) is usually chosen as its representative temperature. An alternative is the integral mean temperature along the borehole depth, which may be determined by numerical integration of Eq. (4).

In Eqs. (3) and (4), λ_s, C_s, R_b are three unknown variables. C_s, λ_s are thermal properties to be estimated combining with related identification methods in TRT, and R_b can be obtained from physical parameters of GHE.

$$R_b=R_g+\frac{R_p+R_f}{2}=\frac{1}{2\pi\lambda_g}\ln\left(\frac{d_b}{d_{po}\sqrt{nl}}\right)+\frac{1}{2}\left[\frac{1}{2\pi\lambda_p}\ln\left(\frac{d_{po}}{d_{pi}}\right)+\frac{1}{\pi d_{pi}h_f}\right] \tag{5}$$

where the term $(R_p+R_f)/2$ represents the combined thermal resistance of the U-pipe, ignoring the resistance between the two legs, and R_g is the grout thermal resistance. The inside convective heat transfer coefficient,h_f, can be calculated by the Dirttus–Boelter equation [71].

$$h_f\approx 0.023\ \mathrm{Re}^{0.8}\ \mathrm{Pr}^{0.3}\ \lambda_f/d_{pi} \tag{6}$$

ILSM is among the most widely used models for evaluation of TRT data at sufficiently large times because of the fact that the TRT was actually devised on the basis of ILS theory. However, in contrast to ILSM, the FLSM overcomes some limitations of the ILSM: its solution has been expressed as an integral, given zero temperature at the boundary of the semi-infinite medium. The temperature response functions, so-called "g-functions" introduced by Eskilson [64], are based on the solution of this model for the GHE temperature field at a constant heat load. The g-functions are computed for moderate times and provide an asymptotic approach to the steady-state limit, which is not reached within the ILSM. The FLSM solution for the ground temperature in the vicinity of the midpoint of the BHE depth was shown to be approximately the same as the classical result of the traditional ILSM during the TRT [72]. However, the best solution for applications is given by the mean integral temperature [73]. An exact solution for the temperature averaged over the borehole depth has been approximated, providing analytical formulae for a wide time range that account for the edge effects due to the vertical heat transfer along the borehole. These simple asymptotic expressions based on FLSM for the mean borehole temperature allow flexibility in parametric analysis of the test data. In a sample, the related parameters in Eqs. (3) and (4) are set T_0=15 °C, α_s=0.0018 m^2/h, λ_s=1.4 W/(m. °C, r_b=0.055 m, and q_l=60 W/m, borehole wall temperatures T_b corresponding to R_b=0 (m °C)/W in Eqs. (3) and (4) can be calculated respectively and compared when borehole depths are set 50 m, 100 m and 150 m. As shown in Fig. 6, it is interesting to notice that an extremum appears in the response of FLSM, which can be accounted for by the influence of the boundary in different borehole depth.

Considering the effect of ambient air temperature variation, the data obtained from the TRT are evaluated and compared by making use of the ILSM and FLSM [52], along with the described method of accounting for the heat rate transmitted to ambient air, characterized by η (Eq. (2)). To find suitable model parameters, Eqs. (3) and (4) (in the time interval of their validity) have been matched, using a regression technique, to the experimental data for the mean temperature of the water as a function of time. Evaluating the same TRT data using FLSM model gives lower values for the ground thermal conductivity than for ILSM, whether or not heat dissipation to ambient air is assumed. In order to evaluate the effect of groundwater advection on heat transfer of GHE, comparison with existing analytical solutions based on FLSM and ILSM is carried out, and a moving finite line source model (MFLSM) which considers groundwater flow and axial effects is developed. Molina-Giraldo et al. [56] conclude that both the

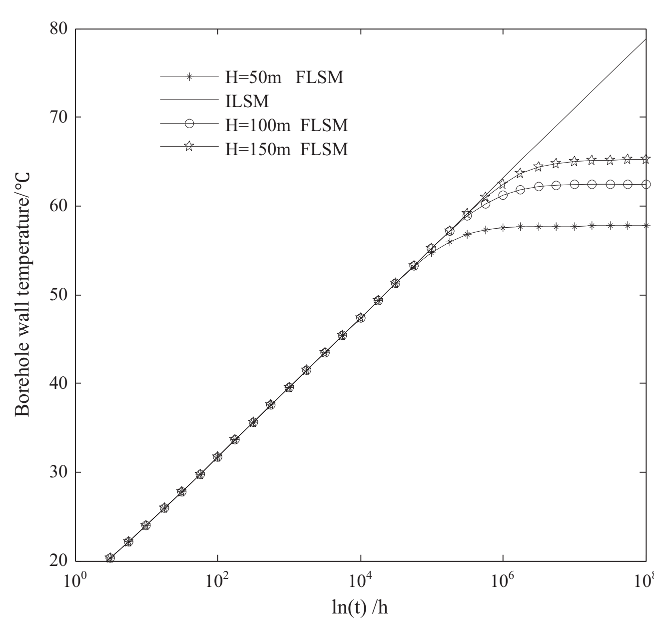

Fig. 6. Calculated borehole wall temperature comparison between ILSM and FLSM.

groundwater flow and the axial heat flow have an effect on the temperature response from a GHE. Losses of heat downwards from the borehole bottom and fix temperature conditions at the surface result in lower temperature changes in the underground surrounding the GHE. This effect becomes more evident and therefore the discrepancy between the MFLSM and MILSM increases with longer simulation time and shorter borehole lengths.

Although line source model (LSM) is characterized by great simplicity and has been proven to be a robust tool in practical applications, it is fast and easy to integrate into parameter estimation program by adopting the late regime temperature history. Therefore, LSM is widely used to estimate thermal properties in TRT. The list of literatures in which LSM is applied is outlined in Table 1.

3.1.2. Cylindrical source model

Cylindrical source model (CSM) extends a line source to a cylindrical source with a constant radius, which is developed by Ingersoll et al. [79] in 1954. The analytical solution of CSM with a constant heat rate is described as

$$T(\tilde{r},Fo)-T_0=\frac{q_l}{\lambda_s\pi^2}\underbrace{\int_0^\infty\frac{e^{-x^2Fo}-1}{x^2[J_1^2(x)+Y_1^2(x)]}[J_0(\tilde{r}x)Y_1(x)-J_1(x)Y_0(\tilde{r}x)]dx}_{G(\tilde{r},Fo)} \tag{7}$$

where $\tilde{r}=r/r_b$; $Fo=\lambda_s t/r_b^2C_s$; J and Y are the Bessel functions of the first and second kind.

In Eq. (7), a G-factor is introduced, which is a dimensionless temperature that depends on the Fourier number, Fo, and a dimensionless radius, $\tilde{r}$. As defined by Carslaw and Jaeger [66] and Yu et al. [80], the expression $G(\tilde{r},Fo)$ is only a function of time and distance from the borehole center. So the temperature at the borehole wall,T_b, can be obtained by setting $\tilde{r}=1$.

Heat transfer outside boreholes is a typical transient heat conduction problem. In contrast, due to the much smaller dimension and thermal capacity, heat transfer inside boreholes is usually treated as steady-state. This assumption has been proved to be appropriate and convenient for most engineering applications. Moreover, thermal resistance is a useful concept for solving steady-state problems. In light of this, the temperature of the circulating fluid in the ground loop can be expressed as [81]

$$T_f(t)=T_0+q_l\left[R_b-\frac{1}{4\lambda_s\pi}G(1,Fo)\right] \tag{8}$$

In Eq. (8), the three unknown variables are also same with Eqs. (3) and (4).

Using the same TRT data, Yu et al. [80] compared estimated results of the ground thermal properties based on CSM and ILSM. The values of thermal conductivity estimated with the CSM are slightly higher than that of the ILSM. The differences are about 13% for the fixed starting time and 6% for the ending time. At the same time, the starting time may play an important role in the thermal

Table 1
Most relevant literature contributions in which the models and parameter identification methods are applied to the TRT.

References	Mathematical model				Parameter identification approach		Unkown parameters				
	ILSM	CSM	Numerical model	Other model	Direct method	Parameter estimation method	λ_s	R_b	C_s	λ_g	Other parameter
[11,17,18–20,32, 33,42,52,74,75]	√				√		√	√			
[26,48]	√					√	√		√		
[28,30]	√				√		√			√	
[29]	√					√	√			√	α_s
[34]	√		√			√	√	√			
[52]	√ FLSM					√	√	√			
[58]	√					√	√	√	√		K, α_s
[69]	√					√	√	√	√		
[76]	√				√		√				α_s
[77]	√					√	√	√	√		
[80]	√	√				√	√	√	√		
[105]	√ MILSM					√	√	√			
[107]	√					√	√	√			
[21]		√				√	√		√		
[81]		√				√	√	√			
[16,82]		√				√	√				
[83]		√			√		√	√			
[84]		√				√	√	√	√		
[85]				√COM		√	√	√			
[45–47]				√COM	√		√	√			
[86]			2D, vertical slice	√COM		√	√		√		
[88]			1D			√	√			√	
[50,89,90]			1D			√	√	√			
[13,51,91]			2D, horizontal slice			√	√			√	
[78]			2D, horizontal slice			√	√				
[57,92,94]			2D, horizontal slice			√	√	√			
[95,96]	√		3D		√	√		√			
[97]			3D			√	√		√		
[98]			3D			√	√		√	√	C_g
[49]			DST(1D, 2D)	√Eskilson's model		√	√	√			
[103]			DST(1D, 2D)			√	√		√		

resistance estimated in the CSM, especially in initial stage of the test because of transient borehole resistance. More literatures applying CSM are listed in Table 1.

3.1.3. *Composite model*

Considering the effect of the thermal storage of the circulating fluid on the early-time loop temperature in TRT, Shonder and Beck [85], Beier and Smith [41] developed a composite model (COM) of GHE where the actual borehole geometry is represented by a simplified, radially symmetric geometry. As illustration of COM is shown in Fig. 7, the U-pipe is replaced by a single pipe with an effective radius of r_{ef}. Shonder and Beck have included a fluid film to represent the thermal resistance between the fluid and inside wall of the pipe. Beier and Smith do not explicitly account for the film resistance, but instead the value, is implicitly taken into account in the value of r_p, and developed an analytical solution to the COM. At the same time, the COM was applied in the interrupted in situ test [45–47]. The COM captures the important heat transfer mechanisms and is one dimensional (radial coordinate), which allows the model to be evaluated quickly by related identification methods on a computer. Based on the COM, Wagner and Clauser [86] used GroenHolland VB [87] to estimate thermal conductivity and thermal capacity in TRT. The literatures applying COM are listed in Table 1.

3.2. *Numerical approaches*

Except for the analytical models, more promising approaches to improve the predictive capabilities of the TRT can be found in the parameter identification procedures supported by numerical models. An important advantage of the numerical models is that it can be easily improved to include some aspects of a real TRT. Among these aspects are: the presence of heat power and fluid flow rate fluctuations, a non-uniform heat power supply, the boundary condition of a constant inlet temperature and the non-homogeneity of the ground. On the other hand, the numerical model is more complex because it requires the system's geometry to be accurately known. Numerical models have served as research tools, and are widely used to analyze routine borehole tests as the previously discussed models. The literatures applying numerical models are listed in Table 1.

3.2.1. *Numerical one-dimensional model*

A numerical model of GHE in which a spatially one-dimensional description is adopted to describe the TRT was validated by Shonder and Beck [88]. The finite-difference solution of the Fourier equation is obtained in the soil domain, and the fluid heat transfer in the pipes is regarded as a steady-state phenomenon by considering the heat capacity of the fluid as lumped into a “film.” The presence of the grout and the geometric arrangement of the pipes are modeled as a single pipe of an effective radius. The estimated values of the thermal conductivity of both grout and soil and the borehole resistance were in good agreement with independent measurements [85] and with values obtained by the LSM and CSM. Gehlin and Hellström [89] presented a one-dimensional finite-difference numerical model and compared this model with three different analytical models. With respect to the numerical model, they observed that, as expected, the one-dimensional model is unable to capture the short-term thermal response of GHE. In order to investigate GHE for groundwater influences, Gustafsson and Westerlund [50] used a numerical axisymmetric heat conduction model to treat the borehole as an annulus in TRT. Moreover, a simple one-dimensional model [90] of the borehole was used to further study the effect of convection and phase change while the temperature was decreased below freezing point. The test and the model show large variations in the borehole thermal resistance.

3.2.2. *Numerical two-dimensional model*

Some approaches are available in literature in which the spatial dependence of the temperature field is described by adopting a two-coordinate system. Most of these methods adopt either a “horizontal slice” or a “vertical slice” approach.

In the vertical slice approach, the heat diffusion is invariant under spatial rotation about the z-axis of the vertical BHE, and therefore, only the z and r dependences are considered. Wagner and Clauser [86]estimated the soil thermal conductivity and heat capacity per unit volume through a parameter estimation procedure coupled with a numerical transient two-dimensional model.

Under the horizontal slice approach, the r and θ dependences of the temperature field are accounted for, but axial effects are disregarded. Austin et al. [13] and Spitler et al. [91] coupled the parameter estimation with a two-dimensional thermal model, and Austin et al. [13] validated this methodology with the aim of simultaneously estimating the thermal conductivities of both the soil and grout by comparing the results regarding a medium scale laboratory experiment with independently measured values, and they observed a maximum deviation of approximately 2.1%. Combining parameter estimation method, Yu and Fang [78] use two-dimensional unsteady thermal model to estimate thermal conductivity in TRT. The two-dimensional approach, also considered by Yavuzturk et al. [92], consists of approximating the BHE geometry as a “pie sector” lying on a plane orthogonal to the BHE axis. By considering a non-symmetric distribution between the two legs of the U-pipe, the convection resistance associated with the fluid flow is incorporated into the pipe's wall resistance, and a

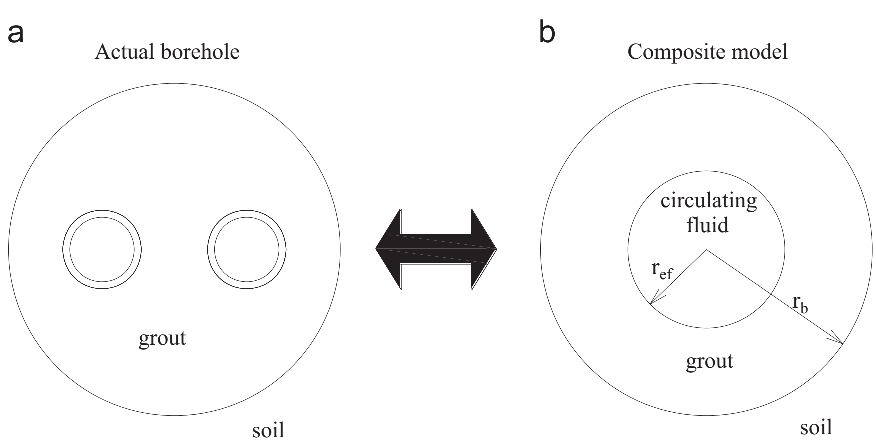

Fig. 7. (a) Geometry of actual borehole and (b) composite model of borehole.

time-varying heat flux is assumed to enter through the pipe wall. Valentin Wagner et al. [57] developed a two-dimensional high-resolution finite element model in FEFLOW 5.4 [93] to predict the complex heat transfer between the several parts of the BHE (heat carrier fluid, pipe wall and grout material), the porous medium, and the moving groundwater. Raymonda et al. [94] developed a two-dimensional horizontal slice of GHE during TRT, numerical model results suggest that the borehole thermal resistance is best evaluated in the field during a conventional TRT using a combination of heating and recovery data.

3.2.3. Numerical three-dimensional model

Among the numerical models, the three-dimensional model is widely applied in heat transfer analysis of GHE. In TRT, the three-dimensional models have been mostly used to generate synthetic TRT data to validate the accuracy of estimated thermal properties of GHE. Signorelli et al. [44] developed a three-dimensional model of GHE in the FRACTure environment, which can accurately simulate the thermal transport in the U-pipe by special one-dimensional pipe elements surrounded by three-dimensional matrix elements. They implemented this model with the usual LSM estimation procedure to generate synthetic TRT response data that enable evaluating the effects of heterogeneous subsurface conditions and groundwater movement. By tuning the soil thermal conductivity, the model's outcomes were compared to experimental TRT data. Marcotte and Pasquier [95] built a three-dimensional model of GHE in the COMSOL Multiphysics environment, In their model the convective resistance between the pipe wall and the fluid flow was neglected. The main outcome of this model is a new definition of the average fluid temperature, which is employed in the usual estimation procedure based on the LSM. Thanks to this improvement, the LSM enables one to better estimate the borehole thermal resistance. Lamarche et al. [96] also implemented a complete three-dimensional model in the COMSOL Multiphysics environment where fluid flow in the pipe is modeled as a one-dimensional problem by using the classical advection equation. The thermal response of this model to a constant heat power is processed with the usual estimation procedure based on LSM in order to estimate soil conductivity and borehole resistance. The results show some limits of LSM in the prediction of the system's properties. In the study conducted by Lee [97], a modified three-dimensional finite difference model for the borehole GHEs of GSHPs was developed which accounted for multiple ground layers with different thermal properties in the borefield at no groundwater flow. The present model was used to investigate the impact of ignoring ground layers in TRT analysis and the subsequent system simulation. It was found that the adoption of an effective ground thermal conductivity and an effective ground volumetric heat capacity for a multi-layer ground determined from a TRT analysis led to very little error in the simulated long term system performance under various ground compositions investigated.

Bozzoli et al. [98] developed a numerical three-dimensional model of GHE coupled with parameter estimation procedures applied to experimental data under an inverse problem approach. Furthermore, a two-step parameter estimation procedure (TSPEP) based on the model of the geothermal system was presented. The procedure was applied to both simulated and experimental standard TRT data in order to restore the grout and soil thermal conductivities and volumetric heat capacities. The TSPEP is essentially a two-step process. Based on the Gauss Linearization Method, further iterations of these two steps can be used to improve the accuracy of the procedure. Li Yong et al. [99] developed a fully three-dimensional equivalent rectangular numerical model, and average heat flux per unit length and short-circuiting loss rate were investigated how the short-circuiting influences on the overall heat transfer in GHE. The lower water flow velocity would lead to greater short-circuiting loss rate and smaller average heat flux per unit length as the fluid in the pipe is laminar. The average heat flux per unit length increases and the short-circuiting loss rate drops quickly with flow velocity increasing from 0.1 m/s to 0.5 m/s, but it does not mean that the higher flow velocity would improve the overall heat transfer capacity of GHE, when the flow velocity is 0.9 m/s ($Re = 27{,}950$), the outlet temperature and average heat flux per unit length and short-circuiting loss rate are almost unchanged. By comparing the arithmetic average fluid temperature and integral average fluid temperature, it was found that the lager short-circuiting loss rate would lead to greater error for effective subsurface conductivity estimation.

3.2.4. Duct storage system model (DST)

In 1991, Hellström [100] proposed a simulation model for ground heat stores, which were densely packed ground loop heat exchangers used for seasonal thermal energy storage, and it was applied in TRNSYS as the model of GHE [101]. The duct storage system model (DST) divides the ground storage volume with multiple boreholes into two regions: one is the volume that surrounds a single borehole, described as the ‘local’ region; the other is called ‘global’ region, which denotes the ground volume between the bulk of the heat store volume and the far field. A two-dimensional finite difference scheme is used to solve the ground temperature in the ‘global’ region while the one-dimensional numerical method is employed to calculate the temperature in the ‘local’ region. In TRT, Witte and van Gelder [49] adopted DST to calculate the borehole response, and the parameter estimation procedure was carried out using the GenOPT package [102]. Based on DST, Zhang et al. [103] proposed the simulation-optimization approach for determining the optimal thermal conductivity and heat capacity of rock-soil using Hooke–Jeeves algorithm [102]. Furthermore, the optimal result was applied in the different GHE model (FLSM, CSM, DST), and the three groups of simulated average water temperature were compared with test values, the result showed temperature difference quadratic sum corresponding to DST model was minimum.

3.3. Combining approaches

Because the one-dimensional model of LSM and CSM neglect the axial heat flow along the borehole depth, Eskilson presented the finite length line source model (FLSM) of GHE [64]. In Eskilson's model, the ground is assumed to be homogeneous with constant initial and boundary temperatures, and the thermal capacitance of the borehole elements such as the pipe wall and the grout are neglected. At the same time, the numerical finite-difference method is used on a radial–axial coordinate system to obtain the temperature distribution of a single borehole with finite length. The final expression of the temperature response at the borehole wall to a unit step heat pulse is named *g*-function, and it is essentially the dimensionless temperature response at the borehole wall, which was computed numerically. For TRT, the important achievement of Eskilson's model is that the sequential temporal superimposition was used to calculate the temperature response (i.e. g-functions) to any arbitrary heat rejection/extraction which can be decomposed into a set of single pulses. In other words, the overall temperature response of the GHE to any heat rejection/extraction at any time can be determined by the special and temporal superimpositions. Witte and van Gelder [49] adopted Eskilson's model to calculate the borehole response on the platform of TRNSYS, and parameter estimation procedure was carried out using the GenOPT package [102]. The procedure

proceeds by having the model calculate the temperature response, using the previously calibrated values for soil conductivity and borehole resistance up to the pulse that is currently being calibrated. The calibration error is defined as the sum of the squared differences between the measured and the calculated GHE return temperature. For the pulse currently being calibrated, different parameter values are selected and the error calculated repeatedly until the GenOPT optimization algorithm has identified the parameter values yielding the minimum error.

3.4. Discussion on the mathematical models of GHE

The modeling of the GHE in TRT has undergone many improvements since it was first formulated. As shown in Table 1, the various models suggested in literature for TRT analysis were applied in relation to the information extracted from the input data, represented by the experimental temperature time history.

As a drastically simplified approximation of GHE, the ILSM represents a starting point that provides a simple and rapid tool for estimating the soil thermal conductivity and the borehole thermal resistances, several points limit its predictive capability. These limitations are mainly related to the fact that other important system parameters, such as soil volumetric heat capacity and grout thermal properties, must be considered as known inputs in the estimation procedure. FLSM was developed by researchers which consider the influences of the finite length of the borehole and the ground surface as a boundary, and it makes the mean borehole temperature (Eq. (4)) computed much faster than the numerical models of the same heat conduction problem in the semi-infinite domain with long duration in TRT. The CSM is more complex analytical model which takes into account the finite dimensions of the heat source. In the CSM, the borehole is assumed as an infinite cylinder surrounded by homogeneous medium with constant properties, i.e. the ground. It also assumes that the heat transfer between the borehole and soil with perfect contact is of pure heat conduction. However, the expression G-function (Eq. (7)) is relatively complex and involves integration from zero to infinity of a complicated function, which includes some Bessel functions. Under a comparative approach, it must be noted that analytical models, particularly the LSM and CSM, show the advantage that they are fast and easy to use and allow the estimation of the soil thermal conductivity and of the borehole thermal resistance by adopting the late regime temperature history. At the same time, the straightforward algorithm deduced from the analytical models can be readily integrated into parameter estimation program, which also makes the analytical models popular. However, this simple approach is not able to model the borehole geometry since the heat source is lumped in a line or a cylindrical source placed in the system axis.

As for numerical models in TRT, it can offer a high degree of flexibility and accuracy (especially on short-term scales) compared with the analytical models when the detailed geometrical configuration and thermal properties parameters in GHE are accurately known. Furthermore, for TRT, numerical models enable more complex phenomena to be taken into account: additional transport mechanisms other than conduction (for instance, groundwater advection within the soil), variable heat flow rate applied to the carrier fluid, variable mass flow rate of the fluid and temperature oscillations of the soil surface. In the application of numerical models, more awareness on the underlying physical phenomena and, consequently, more expertise in both the numerical computation heat transfer and fluid dynamics and parameter estimation procedures are required, and that, most of models using polar or cylindrical grids may be computationally inefficient due to a large number of complex grids, which make the models inconvenient to be incorporated directly into parameter estimation program, unless the simulated data are pre-computed and stored in a massive database.

4. Parameter identification methods

The identification of the unknown thermal properties is achieved through a comparison between the raw data for the time history of the average fluid temperature, experimentally acquired directly from TRT, and the corresponding values predicted by related mathematical models for GHE. The identification of thermal properties using measured temperature values is a well-known inverse heat conduction problem, and the methodologies adopted in literature to handle TRT data can be classified into two main methods, the first one is named as direct method that yield estimate of thermal properties directly without any iterative methods, and the second one depends on the related mathematical models for GHE that are generally implemented through iterative methods. The different identification methods are applied in the literatures shown in Table 1.

4.1. Direct method

As above description, groundwater plays an important role in TRT, which influences the identification of related ground thermal properties. However, in ILSM, the ground is regarded as an infinite medium with an initial uniform temperature, in which the borehole is assumed as an infinite line source. The heat transfer in the direction of the borehole axis, including the heat flux across the ground surface and down the bottom of the borehole, is neglected. The heat conduction process in the ground is, therefore, simplified as one-dimensional one. The mean temperature of the circulating fluid in the ground loop as a function of time t with a constant heat injection q_l is described in Eqs. (3) and (4), and it can be rewritten in a linear form as:

$$T_f(t) = k\ln(t) + b \tag{9}$$

where $k = q_l/4\pi\lambda_s$, the thermal conductivity can be determined from the slope of the line resulting when plotting the fluid temperature against $\ln(t)$. Moreover, the value of the thermal conductivity calculated leads to a number of thermal resistances of GHE, one for every pair of fluid temperature and time, and Beier and Smith [68] recommended the thermal resistances of GHE can be calculated as:

$$R_b = \frac{1}{4\lambda_s\pi}\left[\frac{T_{f,1\ h} - T_0}{k} - \ln\left(\frac{4\lambda_s t_{1\ h}}{\gamma r_b^2 C_s}\right)\right] \tag{10}$$

where $T_{f,1\ h}$ represents the value of Eq. (10) at one hour, $t_{1\ h}$. Generally, direct method has been widely applied to determine the two main parameters necessary for the design of GCHPs, i.e., the soil thermal conductivity and the borehole thermal resistance. However, some important limitations become apparent from direct method's application to field tests. At least two drawbacks exist. Firstly, the start of the linear trend is not always apparent for every temperature curve because the GHE model ignores the difference between the grout and soil thermal capacities, as well as the thermal capacities of circulating fluids. Secondly, the method ignores the effects caused by variable heat input rates which often occur because of electrical power outages, electric heat failures, or other unexpected events.

4.2. Parameter estimation method

Except for direct method, parameter estimation methods are popular in the identification of the unknown thermal properties by use of TRT data. The estimation procedure is generally

constructed iteratively, with the aim of forcing a match between the theoretical predictions from related mathematical models of GHE and the TRT data by tuning system properties. Parameters estimation usually covers several basic problems. The first problem is the choice of the objective function to be minimized. The second is how to minimize the objective function.

4.2.1. The objective function

The common choice of the function to be minimized is the sum of squares of error (SSE). The objective function for the estimation procedure is given by

$$f = \sum_{i=1}^{n} (T_{\text{ex},i} - T_{\text{sim},i})^2 \tag{11}$$

or the root mean squared error (RMSE) is minimized:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_{\text{ex},i} - T_{\text{sim},i})^2} \tag{12}$$

As shown in Eqs. (11) and (12), the amount of information that can be extracted by this parameter estimation procedure depends on the quality and quantity of the TRT data and on the approximation adopted to mathematical models of GHE. The estimation process is shown in Fig. 8. Based on the analytical approaches or numerical approaches for GHE, more parameters of GHE can be identified by means of parameter estimation method. Of course, more accurate mathematical models for GHE will be welcomed. Table 1 summarizes the related literatures in which parameter estimation methods are applied in obtaining different unknown thermal properties. In Table 1, it was shown that the parameter estimation method has become more and more attractive in recent research on TRT.

4.2.2. The iterative algorithms

In parameter estimation methods, iterative algorithms are important to obtain reasonable properties in doing with nonlinear problem such as heat transfer of GHE. Based on different iterative algorithms, the iterative procedure stops when the unknown parameters show a relatively small increment and the objective function is minimized. Table 2 summarizes the related literatures in which different iterative algorithms are applied in minimizing the objective function. Li and Lai [81] have investigated performances of two advanced iterative algorithms, the Levenberg–Marquardt method and the interior trust region method subject to bounds, the conclusion shows that the interior trust region algorithm with good bounds estimation is a better iterative approach. Iterative procedures without bound constraints, such as the Levenberg–Marquardt algorithm, cannot be used for simultaneously estimating thermal physical properties.

Due to measurement impreciseness and data noise, no perfect fit can be obtained and instead of one optimal parameter combination, it is desirable to also evaluate valid parameter pairs. Validity has to be decided on for each specific case and is

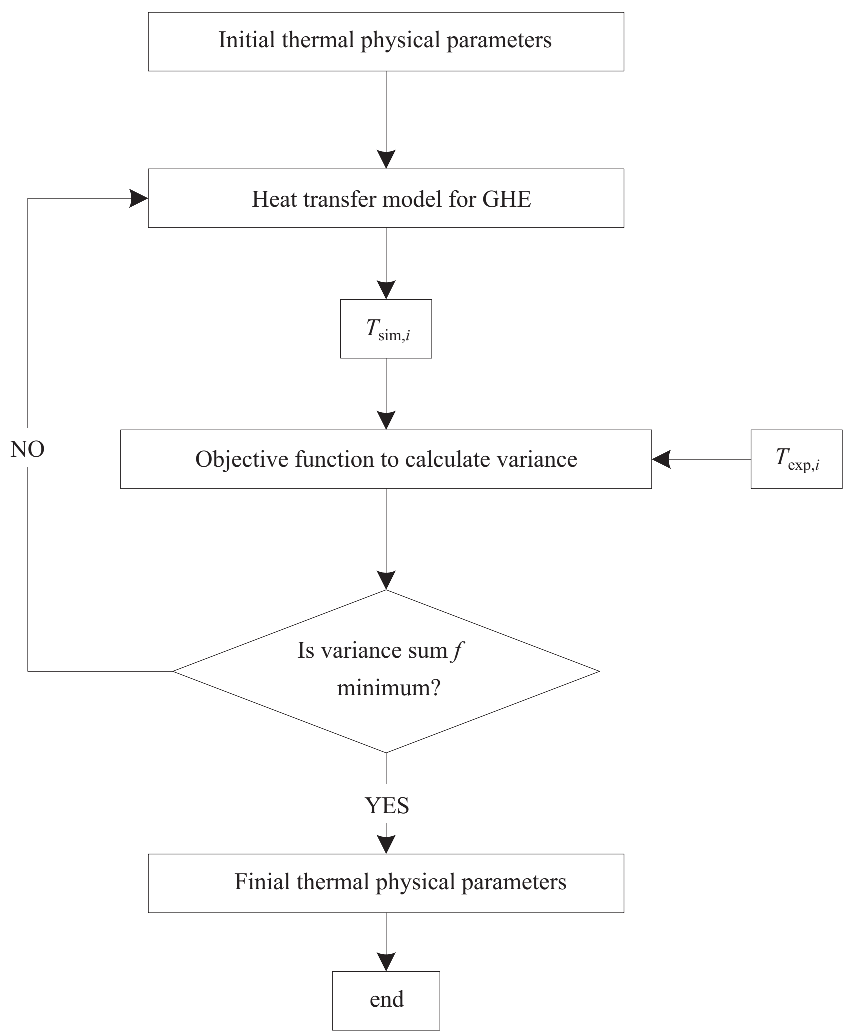

Fig. 8. Calculation process of parameter estimation method.

Table 2
The relevant literature contributions in which iterative algorithms are applied in parameters estimation.

References	Iterative algorithm
[13,34,57,77,80,105,106]	Nelder–Mead simplex search algorithm
[81]	Levenberg–Marquardt
[81]	Interior trust region method subject to bounds
[49,103]	Hooke–Jeeves algorithm
[98]	Gauss linearization algorithm
[107]	Pattern search algorithm

determined by setting a threshold of tolerable RMSE or SSE. In the study conducted by Wagner et al. [34], the acceptable error of the parameter estimation method is set to an RMSE of 0.14 °C based on the typical uncertainty of the temperature difference of 0.14 °C determined by the measurement error of a TRT. By setting a threshold on the RMSE equivalent to the expected measurement error of 0.1 °C (the accuracy of a temperature sensor) [57], the Nelder–Mead Simplex search algorithm is utilized in the parameter estimation technique. When dealing with noisy data, a further stopping criterion based on the Discrepancy Principle [104] should be considered, in which the iterative procedure stops when the residuals between noisy data and the estimated temperature are of the same order of magnitude of the measurement uncertainty.

In further study, as an alternative of finding one optimum solution based on an optimization framework, the Nelder–Mead Simplex search algorithm is widely applied in parameter estimation. However, in such parameter estimation problems, the simple model of GHE may be simply screened by a grid search and all suitable solutions can be recorded, which delivers not only one “global” solution rather than a set of solutions within a tolerance range. In Andrew Chiasson's study [105], multiple apparent local minima are observed in the case of mass transport solution with thermal dispersion. These are described as “apparent” because, while it appears to be a local minimum, it has not yet been established whether or not it is a local minimum through a finer discrete search step. In reality, the measurement error might be different, because of the applied type of sensor, the kind of combination of temperature sensors and/or the temperature dependency of the sensor itself. To inspect whether acceptable locally optimal or close-optimal solutions to the error function exist, multiple randomly initialized Nelder—Mead-based minimization runs are applied. Therefore, considering the ill-posed problems in parameter estimation, it is necessary for TRT to improve the measured accuracy. At the same time, in order to remove the predicted data noise, more feasible accuracy of simplified predictive models of GHE should be developed.

In general, when calibrating models to measurements in natural systems, the complex coupled processes involved often make it impossible that one unique set of valid model parameter values can be determined. For a given tolerance on the RMSE of the GHE model, it is thus suggested to estimate possible parameter ranges and, if they exist, to also extract correlations among different parameters [106]. This insight is in particular valuable for ill-posed problems like the TRT evaluation based on the mathematical model of GHE, where solutions to the inverse problem are non-unique. In general, the three ways are applied to estimate possible parameter range in order to find the optimum solution. The simple way is that the range is more tightly constrained based on realistic values of the parameters which can be found in ASHRAE handbook [25] according to in situ geological setting. This way is applied in Hooke–Jeeves algorithm by Zhang et al. [103] to determine soil thermal conductivity and heat capacity based on DST model of GHE. The second way, some parameters are estimated from the slope and intercept of late temperature measurements on a semi-log plot [68], or from the theoretical ground heat exchanger configuration with analytical solutions before the iterative algorithm is applied in parameter estimation, which helps reduce the non-uniqueness in parameter estimation. In the two studies conducted by Wagner and Clauser [86] and Zhang et al. [107], ground thermal conductivity and heat resistance of GHE is respectively estimated by direct method (Eqs. (9) and (10)) before finding the optimal parameter pairs. The third way, a preventive sensitivity analysis of the unknown parameters on the outlet fluid temperature distribution was presented, which can provide important information on the system's answer with regards to parameter estimation. After performing a systematic sensitivity analysis of the accuracy of the method for thermal capacity determination with respect to data noise and test duration, Wagner and Clauser [86] presented an approach to obtain both the rock thermal conductivity and rock thermal capacity from synthetical TRT data considering realistic data noise. The conclusion shows that the sensitivity of the parameter estimation method is sufficient to obtain the ground thermal properties of a synthetical model even if heat extraction power noise is considered.

Based on the scaled sensitivities analysis of the four parameters (thermal conductivity λ_s,λ_g and volumetric heat capacity C_s,C_g), Bozzoli et al. [98] proposed a versatile two-step parameter estimation procedure (TSPEP) based on the Gauss Linearization Method. They split the estimation procedure into two subsequent steps: first, in the early transient regime, and second, in the late regime. The early transient regime is in the time interval in which the sensitivities of both of the grout thermal properties are significant. In this regime, the parameter estimation procedure provides the possibility to restore λ_g and C_g. These values are inputs in the second step, in which the parameter estimation procedure is applied to the late regime in order to restore λ_s and C_s. To improve the accuracy of this procedure, further iterations of these two steps are considered. The estimated soil thermal properties are input values in a subsequent grout parameter estimation procedure, in which the initial guess values are the estimated grout thermal properties of the previous step. In the implemented TSPEP, the time separation in the soil and grout properties’ estimation partially uncouples the two problems and makes the estimation of these four parameters feasible.

5. Conclusions and recommendations for future work

During the past few decades, a large number of GCHP systems have been widely applied in various buildings around the world due to the attractive advantages of high efficiency and environmental friendliness. The knowledge of underground thermal properties is a prerequisite for correct design of GHE. As an effective way to obtain thermal properties, TRT has been carried out on a GHE in a pilot borehole (later to be part of the borehole field). Since late 1990s, this technology has became more and more popular, and today is used routinely in many countries for the design of larger plants with GHEs, allowing sizing of the boreholes based upon reliable underground data. In this paper, the specifications for in situ TRT, including test setup, minimum duration, heat input rate etc., have been reviewed. Most heat transfer mathematical models currently available for GHE in TRT have been described in details, and the models aiming to identify thermal properties have been compared as well. Finally, this paper focuses on parameter identification methods which are necessary to obtain reasonable properties according to in situ TRT data.

In general, the present overview shows that researchers have obtained the following achievement. Firstly, TRT has developed into a routine tool for investigating ground thermal properties for the design of GHE plants. When high accuracy in the temperature sensing, diligent test setup and sufficiently long test time are guaranteed, TRT has proven reliable and results are reproducible. Secondly, for the mathematical model for GHE in TRT, standard procedure based on LSM and CSM represent a starting point that provides a simple and rapid tool for estimating the soil thermal

conductivity and the borehole thermal resistance, but the approximation in which the model ignores the difference between the grout and soil thermal capacities, as well as the thermal capacities of circulating fluids, limit its predicted capacity. However, the numerical approaches highlights that significant improvements have been achieved, in which the model enable more complex phenomena in in situ TRT to be taken into account: additional transport mechanisms other than conduction (for instance, groundwater advection within the soil), variable heat flow rate applied to the carrier fluid, variable mass flow rate of the fluid, even just the temperature oscillations of the soil surface. Accordingly, the computational cost increases significantly, especially if a three-dimensional model is adopted. At last, parameter identification methods are reviewed. Nowadays, the two identification methods are both applied in TRT, and direct method is a fast tool for obtaining soil thermal conductivity. However, more parameters of GHE can be identified simultaneously by means of parameter estimation method, which make it applied more and more widely in TRT.

Although a great number of researches have focused on the development and application of TRT, there are still a few aspects that need further investigation to broaden and strengthen the applicability of TRT:

(1) More effort should be focused on development of more detailed model for GHE, and the model potentially enables a more accurate estimation of thermal properties of the soil and of the whole GHE in TRT. At the same time, the impact of much more factors, such as vertical temperature profile, groundwater advection and thermal short-circuiting on TRT should be further analyzed so that constraints on plausible thermal parameter ranges in parameters estimation can be strengthened, which can afford reductions in the time required to complete a TRT and then of the operational cost of the experimental procedure.
(2) Considering the operational cost of TRT and complicated in situ test environment, the data analysis study on unexpected events in TRT such as interrupted test, electrical power outage, etc. should be further strengthened, which can improve test efficiency comparing with waiting for initial heat pulse to dissipate before restarting TRT.
(3) Instead of conventional TRTs based on inlet and outlet fluid temperature measurements which limited to giving merely average and global information about the GHE performance, distributed thermal response test (DTRT) by use of distributed temperature sensing (DTS) should be further investigated to obtain detailed information about GHEs, such as vertical variation in local thermal conductivity of layered subsurface, groundwater inflows, undisturbed ground temperature, and borehole thermal resistance. Applications of all this information in design tools, improvement of GHEs and in energy analysis simulations are always the important topics for further research and development of GCHPs.
(4) Except for determining the ground thermal properties, TRTs as an investigation on vertical variability of geological formations should be further studied. Furthermore, advection-influenced TRTs which can be used for integral hydrogeological characterization of the penetrated subsurface should be examined, and another area where further work is required is to make TRT applicable to "thermoactive structure", like energy piles.

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